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Apply FMEA modeling to a floating ecological desalination unit

Keywords

FMEA, reliability block diagram, floating autonomous desalination

Abstract

Water scarcity in small Aegean islands is considered a major problem for their development. On the other hand high potential renewable energy sources are available. Therefore a floating desalination unit was developed in order to treat the problem in an ecological manner. The floating unit has been operating for four years at sea close to a small island. Marine environment and autonomous remote operation led to a more complex design with several sensors and safety mechanisms. This paper illustrates and applies Failure Modes and Effects Analysis (FMEA) modeling to Floating Ecological Desalination Unit. FMEA is based on monitoring data and also taking into account failure dependencies between components during the assessment of desalination system reliability. Then two systems, one with safety mechanisms and one without are analyzed by Reliability Block Diagrams (RBD) and the reliability of each system is computed. The comparison between a simple system and the remote autonomous system illustrates the implications of the additional monitoring mechanisms and the impact of these mechanisms to reliability and risk assessment on the floating wind powered offshore desalination unit.

1. Desalination introduction

The growing population and rising levels of industrialization increase the consumption of water and make necessary the development of new potable water production sources. In order to address this issue efficiently and ecologically, a new approach has been developed in Aegean Islands, which integrates a reverse osmosis (RO) desalination system together with wind turbine and photovoltaic panels [7]. The electricity generated from the wind turbine provides the required energy for reverse osmosis desalination. Wind turbines have been installed in many areas and on islands, but the cost of installation and power transmission to the desalination unit is considerable high, because they are installed far from each other.

On the other hand, desalination units exist in floating structures (e.g. ships, barges), which operate with power produced from energy sources not friendly to the environment. Thus by coupling a desalination

unit with wind turbine on a floating structure the following advantages are achieved:

- reduced cost of connection between the units, since it doesn't require long transmission path,
- possibility of placing the unit far from ridges or villages so it doesn't bother the residents,
- possibility of transporting the unit if required.

The design concept of the floating desalination consists of the main floating structure where the Reverse Osmosis and Wind Turbine generator are mounted. Four appropriate peripheral floaters connected with pipes around the central floating structure provide the required stability. The structure has been optimized in order to establish preliminary performance characteristics, minimize movements from waves, improve operating conditions of the wind turbine and withstand extreme weather conditions.

The power supply to the desalination unit comes from the wind generator without utilization of electricity grid, or any kind of diesel generator. This means that we have a varying power source without constant frequency and voltage. Electrical system components create a stable micro grid suitable for the operation of all equipment despite the significant variations in the wind speed. Therefore the electrical system handles short term variation while the energy management in the control system takes care of the energy balance on longer periods. The wind turbine produces and supplies, through advanced electrical and electronic energy conversion components, energy to the desalination unit that uses reverse osmosis technique as the most appropriate desalination method.

The reverse osmosis desalination is modified in order to eliminate the use of chemicals to treat incoming sea water. Also the dispersion of brine in sea is not detrimental to the environment because the sea currents take away and dissolve the brine continuously. Additionally the system operates at varying available power. Therefore the operation should be stable over a wide range of flow and pressure. In order to maximize output, energy efficiency is important. Therefore energy recovery devices were examined in order to derive the most suitable approach. Research focused on reducing organic and inorganic deposits. Sedimentation increases when flow is not stable and no chemicals are used. Therefore a particular reverse osmosis membrane design was chosen that increases flow over the membranes. In this way concentration polarization is reduced and membranes get fewer deposits. All motor pumps are driven by inverters in order to adjust gradually all operating parameters. Energy recovery is based on pressure exchange of concentrate with feed water and is of revolver type, which provides high energy efficiency.

Each sub system has its local control unit and these units accept commands from a higher level where the master control coordinates all operations. This makes system autonomous. The main components are the wind generator, active rectifier and inverter, wind turbine control, reverse osmosis control, master control and onshore SCADA system. Interconnection of different system includes: low level electrical digital and analog signals, Modbus network, Lonworks, TCR/IP, GPRS connection and VPN. Through master control unmanned autonomous operation is achieved while at the same time the system can be fully tele-operated and remote-monitored if required. During autonomous operation the main controls are power management, energy storage management back up and stand by systems handling. Additionally safety issues like monitoring

of critical parameters alarms and notification mechanism are developed. These innovations have led to improved water production efficiency, lower water production costs and reduced environmental impact with respect on safety and minimum maintenance.

2. Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effects Analysis (FMEA) or FMECA is important in our automated system because it facilitates the identification of potential problems in the design or process by examining the effects of lower level failures. Additionally it is a procedure in product development and operations management for analysis of potential failure modes within a system for classification by the severity and likelihood of the failures. Used as a reliability evaluation technique to determine the effect of system and equipment failures results of [1]. Failures were classified according to their impact on mission success and personnel/equipment safety. Formally developed and applied by NASA in the 1960's to improve and verify reliability of space program hardware. When used during the design stage the aim is to avoid future failures. Later it is used in process control, before and during ongoing operation of the process. The use of FMEA begins, ideally, at the earliest conceptual stages of design and continues through the life of the product or service, the proof found in [2],[10].

The identification of potential failure modes on past experience with similar products or processes is what characterizes a successful activity of FMEA team. Enable the team to mitigate and design out of the system those failures, with the minimum of effort and resource expenditure thereby reducing development time and costs, increased throughput, decreased waste, decreased warranty costs, reduce non-value added operations. It provides detailed insight into the systems interrelationships and potentials for failure, results of [5].

The FMEA team determines, by failure mode analysis, the effect of each failure and identifies single failure points that are critical. Failures are prioritized according to how serious their consequences are, how frequently they occur and how easily they can be detected. It may also rank each failure according to the criticality of a failure effect and its probability of occurring. The FMECA is the result of two steps:

- Failure Mode and Effect Analysis (FMEA)
- Criticality Analysis (CA).

The outcome of an FMEA development is actions to prevent or reduce the severity or likelihood of failures, starting with the highest-priority ones. It

may be used to evaluate risk management priorities for mitigating known threat vulnerabilities as describe in [1]. FMEA helps select remedial actions that reduce cumulative impacts of life-cycle consequences (risks) from a systems failure (fault). Also documents current knowledge and actions about the risks of failures for use in continuous improvement. Before starting with an FMEA, it is important to complete some pre-work to confirm that robustness and past history are included in the analysis.

Then, a block diagram of the system needs to be created. This diagram gives an overview of the major components or process steps and how they are related. These are called logical relations around which the FMEA can be developed. It is useful to create a coding system to identify the different system elements, the proof found in [2], [4]. The block diagram should always be included with the FMEA.

A worksheet needs to be created, which contains the important information about the system. On this worksheet all the items or functions of the subject should be listed in a logical manner, based on the block diagram.

2.1. FMEA Related Definitions

Severity (S) - Severity is a numerical subjective estimate of how severe will be for the whole system or the next part of system the EFFECT of a failure. Determine all failure modes based on the functional requirements and their effects. Examples of failure modes are: Electrical short-circuiting, corrosion or deformation. Each effect is given a severity number (S) from 1 (no danger) to 10 (critical) and specified in the next *Table.1*.

Table 1. Severity ranking (FMEA-FMECA.com adopt by authors)

Effect	Severity of effect	Ranking
Hazardous – without warning	Very high, the failure may result unsafe operation and possible injury, product becomes inoperative, without warning.	10
Hazardous – with warning	Very high, product becomes inoperative, the failure may result unsafe operation and possible injury, with warning.	9
Very high	Item inoperable, causes a loss of primary function.	8
High	Item operable, but at reduced level of performance.	7

Moderate	Item operable, but convenience item(s) inoperable.	6
Low	Item operable, but convenience item(s) operable at reduced level of performance.	5
Very low	Affects very little of the system, defect noticed by most customers.	4
Minor	Affects very little of the system, noticed by average customer	3
Very minor	Only noticed by discriminating customers.	2
None	No danger, no effect	1

Occurrence (O) - Occurrence or sometimes termed likelihood is a numerical subjective estimate of the likelihood that the cause, if it occurs, it is necessary to look at the cause of a failure mode and how many times it occurs, will produce the failure mode and its particular effect. This can be done by looking at similar products or processes and the failure modes that have been documented for them. A failure mode is given an occurrence ranking from 1–10. This step is called the detailed development section of the FMEA process.

Table 2. Occurrence ranking (FMEA-FMECA.com adopt by authors)

Probability of Failure	Possible Failure Rates	Ranking
Very high: failure I almost inevitable	≥ 1 in 2	10
	1 in 3	9
High: repeated failures	1 in 8	8
	1 in 20	7
Moderate: occasional failures	1 in 80	6
	1 in 400	5
Low: relatively few failures	1 in 2000	4
	1 in 15000	3
Remote: failure is unlikely	1 in 150000	2
	≤ 1 in 1500000	1

Detection (D) - Detection is sometimes termed effectiveness. It is a numerical subjective estimate of the effectiveness of the controls to prevent or detect the cause or failure mode before the failure occurs. If the assumption is that the cause has occurred. The assigned detection number measures the risk that the failure will escape detection. A high detection number indicates that the chances are high that the failure will escape detection, or in other words, that the chances of detection are low. A high detection

number indicates that the chances are high that the failure will escape detection, or in other words, that the chances of detection are low.

Table 3. Detection ranking (FMEA-FMECA.com adopt by authors)

Detection	Criteria: likelihood of detection by design control	Ranking
Absolute uncertainty	Design Control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode, or these is no Design Control.	10
Very remote	Very remote chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	9
Remote	Remote cause the Design Control will detect a potential cause/mechanism and subsequent failure mode.	8
Very low	Very low chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	7
Low	Low chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	6
Moderate	Moderate chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	5
Moderately high	Moderately high chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	4
High	High chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	3
Very high	Very high chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	2
Almost certain	Design Control will almost certainly detect a potential cause/mechanism and subsequent failure mode.	1

Risk Priority Number (RPN) - Provides an alternate evaluation approach to Criticality Analysis. The risk priority number provides a qualitative numerical estimate of design risk. RPN is defined as the product of the three previous independently

assessed factors: Severity (S), Occurrence (O) and Detection (D). $RPN = (S) * (O) * (D)$, the proof found in [4], [10].

Normally large RPN values indicate more critical failure modes. But it should be noted that in assessing risk is not enough to take into account only the high RPN because it can lead to costly mistakes. High Severity failure modes should be given serious consideration and with it to evaluate the system regardless of their overall RPN values.

The same failures that detect in autonomous desalination system applied on the single system. Also in consideration of severity, the detection method and the occurrence of each one system separately calculate a total RPN number in respect of detection method and the effect on system. The total RPN for single system its 657 and the total RPN for autonomous system its 226 as illustrate on *Table 4* and *Table 5* which are a sample of FMEA table with recording data

Table 4. Total RPN in FMEA table on a single desalination system

System part	Function	Failure mode	S	O	Detection method/ Current controls	D	RPN (Risk priority number)	End effect on product or Other Systems
Air compressor	supply air to open air motivated valves	air compressor no rotation or no air supply	9	3	observe at system press air	3	81	no start the hole desalination system
(FWF): Sea water inlet filter before feed pump	clean & supply sea water	no water across filter	4	1	no water to SWFP	4	16	no start the hole desalination system
Sea water feed pump (SWFP)	supply sea water	feed pump no rotation or no water supply	8	1	no water to SF	5	40	no start the hole desalination system
High Pressure Pump (HPP)	supply sea water to RO	HPP pump no rotation	8	3	observe to RO no water	4	96	no work RO & ERD
Reverse Osmosis (RO)	clean sea water to potable	mebrane fail	17	5	test and observe potable water	4	340	no drincable water orno work ERD
Boosters pump (BPP)	increase the press of water supplied from ERD	BPP pump no rotation	7	4	observe no water discharge	3	84	no start RO & ERD
TOTAL RPN							657	

Table 5. Total RPN in FMEA table on an autonomous desalination system

System part	Function	Failure mode	S	O	Detection method/ Current controls	D	RPN (Risk priority number) SxOxD	End effect on product or Other Systems
Air compressor	supply air to open air motivated valves	air compressor no rotation or no air supply	9	3	PSA	1	27	no start the hole desalination system
PSA (Pressure Air Switch)	observe air pressure supply to valves and EPFD	fail to observe the pressure decrease	7	1	observe from control panel	1	7	no valves work, fluctuation on system
(FWF): Sea water inlet filter before feed pump	clean & supply sea water	no water across filter	4	1	F11,PS1	2	8	no start the hole desalination system
Sea water feed pump (SWFP)	supply sea water	feed pump no rotation or no water supply	8	1	F11,PS2	1	8	no start the hole desalination system
High Pressure Pump (HPP)	supply sea water to RO	HPP pump no rotation	8	3	PS2	1	24	no work RO & ERD
Excessive Press Fluctuation (EPF) DUMPER	reduce fluctuation to system press after	no reduce fluctuation	4	0	PS2	2	0	fluctuations to system water press &
Reverse Osmosis (RO)	clean sea water to potable	membrane fail	17	5	PS3, PS4, N12, F13	1	85	no drinkable water or no work ERD
Boosters pump (BPP)	increase the press of water supplied from ERD	BPP pump no rotation	7	4	PS2	1	28	no start RO & ERD
F13: flow indicator at pure water line	observe flow rate	fail to observe flow rate	6	2	PS3, observe control panel	1	12	wrong mesures
PS3: Permeate water press stop plant above 3 bar	observe potable water press	fail to observe pressure rise	9	1	F13, PS4, observe of Control panel	1	9	RO work without correct press
T12: permeate water temperature	observe temperatur of permeate water	fail to observe temperature rise	9	1	observe from control panel	1	9	RO work with high temperature
N12: inlet water conductivity meter	observe water salinity	fail to observe water salinity rise	9	1	observe from control panel	1	9	wrong mesures
TOTAL RPN							226	

On offshore floating desalination system the severity failures modes in autonomous system include also the severity failures modes of the simple system. Therefore by comparing the total RPN resulting of the previous tables concludes that the autonomous system has a lower RPN because the effects of automation reduce the probability of detection failure.

3. Reliability modeling

Probabilities of events that affect system's operability are calculated to form an estimate of system reliability. The reliability of the system is derived from individual components reliability

results of [11]. Systems are most commonly described through either in series connection or in parallel connection of components. In case of series connection, each element of the system is required to operate correctly so that the system operates correctly. In case parallel system connection, when a parallel component fails the reliability of the overall system is reduced, but the system remains completely or partially functional, the proof found in [4], [10].

Coverage of a fault derives approximately by examining the design, and making reliable estimates. This number is difficult to determine exactly because it is based on real function and often unpredictable phenomena. In order to estimate reliability we examine the faults of the desalination system in respect of failures that have been recorded in the past four years. We construct a block diagram results of [8] and make a comparative analysis between two systems: one that works with safety and monitoring mechanisms of critical parameters and second common one without all these components.

3.1. Functional block diagram

In consideration of the floating ecological desalination plant, which produces potable water, the system consists of the following parts:

1. Air compressor for the production of pressurized air, which controls the air driven valves.
2. Valves which open with compressed air:
 - FV : Sea Water inlet valve,
 - VA1: Valve after No1 filter,
 - VA2: Valve After No2 filter,
 - VA3: Valve for feeding water to Energy Recovery Device,
 - VA4: Valve for feeding brine-water to Energy recovery Device.
3. Motor valves:
 - MV1: Opens and control press when working ERD,
 - MV2: closed at normal operation, opens when ERD fail.
4. Filters:
 - Feed water filter (FWF): Sea water inlet filter before feed pump,
 - Sand Filter (SF),
 - Filters 1,2 after sand filter (F1,F2).
5. Sea water feed pump (SWFP).
6. High Pressure Pump (HPP), reciprocating pump to achieve the working pressure for reverse osmosis (RO).
7. Excessive Pressure Fluctuation dumper (EPFD), protect and prevent the RO unit and system from press fluctuation of reciprocating high

pressure pump.

8. Energy Recovery Device (ERD), increase the press of feed water parallel with high pressure pump and working with water from brine discharge of reverse osmosis.
9. Boosters pump (BPP). Increase the water press to water that discharged from ERD.
10. Reverse Osmosis (RO) desalination unit with 10 membranes-elements working parallel.

3.2. Block diagram

The block diagram as describe in [5], of the system is defined through a combination of both series and parallel connections of subsystems.

An air compressor produces pressurized air to open the air driven valves in the system. Sea water comes through FV valve, which open by compressed air. Sea water pumped by sea water feed pump (FWFP) passes through the feed water filter (FWF). Then passes through sand filter (SF) and a parallel arrangement of filter 1 (F1) and valve 1 (VA1) or filter 2 (F2) and valve 2 (VA2). These filters clean feed water to protect the membranes at reverse osmosis system.

Then a reciprocating high pressure pump (HPP) increases the sea water pressure to provide the working pressure to reverse osmosis (RO). To protect the system and the prevent of pressure fluctuation of reciprocating pump on system and the membranes, a dumper for excessive pressure fluctuation is placed between high pressure pump and RO. Pure potable water produced from RO is stored in storage tank and then pumped to the island.

To improve energy efficiency, an energy recovery device (ERD) is arranged parallel with RO modules. This works with high pressure brine discharge of the RO modules. The pressure of brine revolves a ceramic impeller that exchanges pressure with sea water from feed line. To obtain the working pressure of RO, the discharge of feed sea water passes through a boosters pump.

The function of energy recovery device is achieved by supplying brine discharge of RO through motor valve 1 (MV1). When MV2 closes, brine is discharged across valve VA3 to ERD, while MV1 controls the pressure of ERD. In addition when MV2 is open, valve VA3 closed and MV1 closed, ERD is not operating and the brine discharged. Without ERD the RO produces water, but cannot achieve maximum production nor energy saving.

The reliability block diagram for the single system reliability illustrates in *Figure 1*.

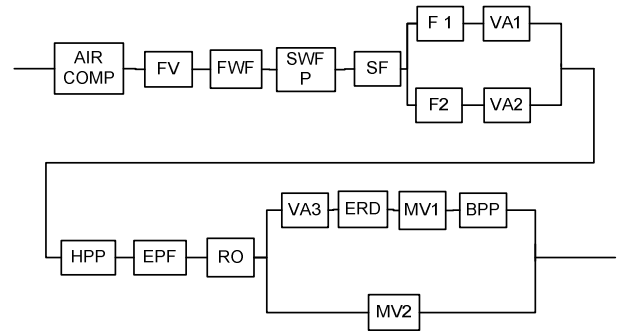


Figure 1. Illustrate the reliability block diagram for single system.

A reliability block diagram that contains both series and parallel components can be reduced to a single series diagram by replacing each of the parallel portions of the system with an equivalent single element that has the same reliability as the parallel components [6], [10]. In order to discover reliability estimate based on Reliability Block Diagram of the system in fig.1 with arrangement in series and in parallel the logical steps are:

1. Merging of elements VA3, ERD, MV1 and BPP to form the equivalent element (g).
2. Merging of elements MV2 with the equivalent element (g) which form the equivalent element (f).
3. Merging of elements F1 and VA1 to form the equivalent element (e).
4. Merging of elements F2 and VA2 to form the equivalent element (d).
5. Merging of equivalent elements (e) and (d) to form the equivalent element (c).

In order to compute the reliability of entire system we compute the reliability of each subsystem and individual component which are in series and parallel arrangement.

Entire system works for four years $t=35040$ hours and the failure rate denotes as λ_i for each component where i (air comp., FV, FWF, SWFP,.....,MV2). The failure rate found in [5] is

$$\lambda = \frac{\text{failures}}{t} \quad (1)$$

The failure rate λ_i and reliability R as proof in [4], [10], given by equations:
 For series systems

$$\lambda_{\text{series}} = \lambda_1 + \lambda_2 + \dots + \lambda_i \quad (2)$$

$$R_{\text{series}} = R_1(t) * R_2(t) * \dots * R_i(t) = \exp(-\lambda_i) \quad (3)$$

For parallel systems

$$\lambda_{system} = \lambda_1 * \lambda_2 * \dots * \lambda_i \quad (4)$$

$$R_{parallel} = 1 - (1 - R_1) * (1 - R_2) * \dots * (1 - R_i) = 1 - (1 - \exp(-\lambda_1)) * \dots * (1 - \exp(-\lambda_i)) \quad (5)$$

a) The element (g) is a series system constitutes of elements VA3, ERD, MV1, BPP, and has the reliability $R_g(t)$ with failure rate $\lambda_g(t)$. The failure rate calculated from equation (1) and give $\lambda_{VA3}=0$, $\lambda_{EDR}=0$, $\lambda_{MV1}=0$, $\lambda_{EPP}=1,14*10^{-4}$ and can be expressed from equations (2), (3) as

$$\lambda_g = \lambda_{VA3} + \lambda_{ERD} + \lambda_{MV1} + \lambda_{BPP} = 1,14155 * 10^{-4}$$

$$R_g = R_{VA3} * R_{ERD} * R_{MV} * R_{BPP} = 0,999886$$

b) Element (f) is a parallel system constitutes of elements MV2 with the equivalent element (g) and has the reliability $R_f(t)$ with failure rate $\lambda_f(t)$. The system f reliability and failure rate can be expressed from equations (1),(4),(5) as

Table 6. Results for elements failure rate

$\lambda_{MV2} = 0$
$\lambda_g = 1,14155 * 10^{-4}$
$\lambda_f = \lambda_g * \lambda_{MV2} = 0$

Reliability of the parallel system of the two above components from equation (5) is

$$R_f = 1 - (1 - R_{MV2}) * (1 - R_g) = 1$$

c) Merging of components F1, VA1 is series and form the equivalent element (e) with $R_e(t)$, $\lambda_e(t)$, also the composition of components F2, VA2 is series and form the equivalent element (d) with $R_d(t)$, $\lambda_d(t)$.

For the systems e, d, reliability and failure rate from equations (1),(2),(3) can be expressed as

Table 7. Result for elements failures rates and reliabilities.

$\lambda_e = \lambda_{F1} + \lambda_{VA1} = 0$	$R_e = \exp(-\lambda_e)$
$\lambda_d = \lambda_{F2} + \lambda_{VA2} = 0$	$R_d = \exp(-\lambda_d)$

d) The reliability $R_c(t)$ of equivalent element c computed from constitutes of equivalent elements e, d, as a parallel system, and the reliability can be expressed as

$$R_c = 1 - (1 - R_e) * (1 - R_d) = 1$$

The reliability block diagram of the desalination system is shown in Figure 1. By taking the product of each element's reliability, we find that the reliability of the system R_{system} as given from equation (3) is

$$R_{system} = R_{AirComp} * R_{FV} * R_{FWF} * R_{SWFP} * R_{SF} * R_c * R_{HPP} * R_{EPF} * R_{RO} * R_f$$

or from exponential law

$$R_{system} = \exp(-\lambda_{system})$$

In series system the failure rate $\lambda_{system}(t)$ can be added equation (2) so to obtain the failure rate of the desalination system we can write

$$\lambda_{system} = \lambda_{AirComp} + \lambda_{FV} + \lambda_{FWF} + \lambda_{SWFP} + \lambda_{SF} + \lambda_c + \lambda_{HPP} + \lambda_{EPF} + \lambda_{RO} + \lambda_f$$

With failure rate of the components Air Comp., FV, FWF, SWFP, SF, HPP, EPF and RO are in next table

Table 8. Results for elements failure rate as equation (1) is

$\lambda_{AirComp} = 8,56164 * 10^{-5}$
$\lambda_{FV} = 0$
$\lambda_{FWF} = 2,853888 * 10^{-5}$
$\lambda_{SWFP} = 5,70776 * 10^{-5}$
$\lambda_{SF} = 0$
$\lambda_{HPP} = 0$
$\lambda_{EPF} = 0$
$\lambda_{RO} = 3,71 * 10^{-4}$

Then as equation (2)

$$\lambda_{system} = 6,27854 * 10^{-4} \quad (6)$$

and

$$R_{system} = \exp(-\lambda_{system}) = 0,999372 \quad (7)$$

Additionally safety issues like monitoring of critical parameters, alarms and notification or monitoring mechanisms are developed and settled on the system. These are:

1. Pressure switches which are:
 - PSA: Air compressor which provides air pressure to the system.
 - PS1: Activates by water pressure before HHP (high pressure pump), Deactivate when pressure drops below 0,5bar.
 - PS2: controls operating pressure.
 - PS3: Permeate water pressure above 3 bar stops plant.
 - PS4: discharge brine pressure (concentrate after RO) stops plant above 9bar
2. Pressure transmitter:
 - PT: Compares pressure before sand filter and after filter 1,2
3. Temperature indicators protect reverse osmosis membrane from high temperature:
 - TI1: feed water temperature.
 - TI2: permeate water temperature.
4. Conductivity indicators:
 - NI1: inlet water conductivity meter.
 - NI2: after RO conductivity meter
5. Flow indicators:
 - FI1: inlet water flow indicator
 - FI2: flow indicator after REC (Recovery Energy Device)
 - FI3: flow indicator at pure water line

The additional safety issues that change the system reliability illustrates in *Figure 2*.

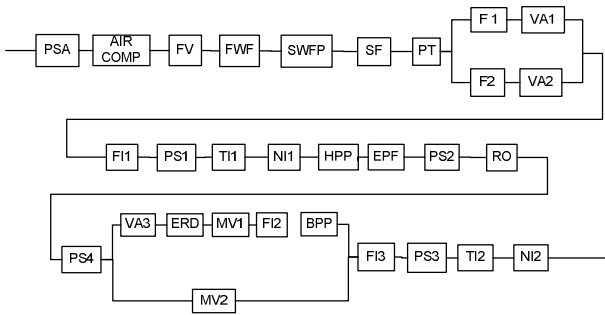


Figure 2. Illustrate RBD (reliability block diagram) with additional safety issues.

By taking the product of the elements reliabilities, we find that the reliability of the system with supervision elements R'_{system} is given by:

$$R'_{system} = R_{PSA} * R_{AirComp} * R_{FV} * R_{FWF} * R_{SWFP} * R_{SF} * R_{PT} * R_c * R_{FI1} * R_{PS1} * R_{TI1} * R_{NI1} * R_{HPP} * R_{EPF} * R_{PS2} * R_{RO} * R_{PS4} * R'_f * R_{FI3} * R_{PS3} * R_{TI2} * R_{NI2} = \exp(-\lambda'_{system})$$

In series system the failure rate $\lambda'_{system}(t)$ can be added so to obtain the failure rate of the desalination system we can write

$$\lambda'_{system} = \lambda_{PSA} + \lambda_{AirComp} + \lambda_{FV} + \lambda_{FWF} + \lambda_{SWFP} + R_{SF} + R_{PT} + R_c + R_{FI1} + R_{PS1} + R_{TI1} + R_{NI1} + R_{HPP} + R_{EPF} + R_{PS2} + R_{RO} + R_{PS4} + R'_f + R_{FI3} + R_{PS3} + R_{TI2} + R_{NI2}$$

The failure rate for elements $\lambda_{AirComp}$, λ_{FV} , λ_{FWF} , λ_{SWFP} , λ_{SF} , λ_c , λ_{HPP} , λ_{EPF} , and λ_{RO} is equal to the previous system as result the reliability of elements is correspondingly $R_{AirComp}$, R_{FV} , R_{FWF} , R_{SWFP} , R_{SF} , R_c , R_{HPP} , R_{EPF} , and R_{RO} . For the rest elements the failure rate and reliability is illustrated in next table as equations (1), (2), (3), (4), (5):

Table 9. Result for elements failures rates and reliabilities.

$\lambda_{element} = \frac{failures}{t}$	$R_{element} = \exp(-\lambda_{element})$
$\lambda_{PSA} = 2,85388 * 10^{-5}$	$R_{PSA} = 0,999971$
$\lambda_{PT} = 0$	$R_{PT} = 1$
$\lambda_{FI1} = 0$	$R_{FI1} = 1$
$\lambda_{PS1} = 0$	$R_{PS1} = 1$
$\lambda_{TI1} = 0$	$R_{TI1} = 1$
$\lambda_{NI1} = 0$	$R_{NI1} = 1$
$\lambda_{PS2} = 0$	$R_{PS2} = 1$
$\lambda_{PS4} = 0$	$R_{PS4} = 1$
$\lambda'_g = \lambda_{VA3} + \lambda_{ERD} + \lambda_{MV1} + \lambda_{FI2} + \lambda_{BPP} = 1,14155 * 10^{-4}$	$R'_g = 0,9998858$
$\lambda'_f = \lambda'_g * \lambda_{MV2} = 0$	$R'_f = 1 - (1 - R_{MV2}) * (1 - R'_g) = 1$
$\lambda_{FI3} = 5,70776 * 10^{-5}$	$R_{FI3} = 0,999943$
$\lambda_{PS3} = 2,85388 * 10^{-5}$	$R_{PS3} = 0,999971$
$\lambda_{TI2} = 2,85388 * 10^{-5}$	$R_{TI2} = 0,999971$
$\lambda_{NI2} = 2,85388 * 10^{-5}$	$R_{NI2} = 0,999971$

Then assume for the system with additional issues is

$$\lambda'_{system} = 7,99087 * 10^{-4} \quad (8)$$

and

$$R'_{system} = \exp(-\lambda'_{system}) = 0.999201 \quad (9)$$

The comparison of results from previous reliability block diagrams equation (7), (9), according the rate of the recorded failures shows that the difference of $R_{system} - R'_{system} = 0,000171$ in the reliable operation is negligible even if the components in autonomous system are more.

The main issue is that safety mechanisms increase the security that required for operate an offshore system.

Conclusions

The offshore desalination plant is composed from many systems, which are different from each other. Additionally new approaches and technologies have been adopted in order to integrate the different components. Therefore safety assessment should cover all possible areas including those where it is difficult to apply traditional safety assessment techniques. This paper analyzes the safety mechanisms that secure the operation of the autonomous offshore desalination system. The application of failure modes and effects analysis modelling and reliability computation of the process based on RBD, demonstrate the impact of safety mechanisms in operation of the floating offshore desalination unit results of equations (6), (7), (8), (9). The computation based on recorded data *Table 4, 5* that gathered during the four years of operation provides the opportunity to increase reliability regarding the integration of the system components. Nevertheless the results show that although safety components of the system slightly reduce reliability, their major effect is to significantly reduce risk, which is most important in remote autonomous operation.

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